DOCUMENT RESUME

ED 282 770 SE 048 196

AUTHOR	Munby, Hugh; Russell, Tom
TITLE	Science Education and the Epistemology of Schools: Neglected Facets of Subject Matter.
PUB DATE	Apr 87
NOTE	11p.; Paper presented at the Annual Meeting of the American Educational Research Association (Washington, DC, April 20-24, 1987).
PUB TYPE	Speeches/Conference Papers (150)
EDRS PRICE	MF01/PC01 Plus Postage.
DESCRIPTORS	Elementary School Science; Elementary Secondary Education; *Epistemology; Foreign Countries; Instructional Improvement; Learning; Philosophy; *Science and Society; Science Curriculum; Science Education; *Science Instruction; Science Teachers; *Scientific Attitudes; *Scientific Literacy; Scientific Principles; Secondary School Science; Teaching Methods

ABSTRACT

Perspectives on the nature of subject matter in science are offered in this paper. It is proposed that science and its context are better viewed as shifting rather than remaining fixed. The rational, moral, and authentic nature of science is explained in reference to education in general and more specifically to the contexts of the science teacher and the individual student. Ideas are presented on: (1) the widening gap between science and "school science"; (2) shifts in an understanding of science's epistemology; (3) science and shifting linguistic contexts; (4) the seductiveness of "science for all"; (5) the epistemology of science; and (6) the challenge of science education. A list of references is included. (ML)

SCIENCE EDUCATION AND THE EPISTEMOLOGY OF SCHOOLS: NEGLECTED FACETS OF SUBJECT MATTER[1]

Hugh Munby and Tom Russell[2]
Faculty of Education
Queen's University
Kingston, Ontario
K7L 3N6

Introduction

The symposium, "Neglected Facets of Subject Matter", of which this paper is a part, is aimed at making problematic the conventional idea that subject matter is fixed. The apparently fixed nature of subject matter leads to the idea that curriculum content is unproblematic, a view that propels both the textbook market and the familiar exhortation that teachers cover the content of the texts.

For science education, the fixed nature of subject matter has been an implicit but potent slogan, essentially prescribing curriculum content for about a century. True, many texts have sections on, or otherwise allude to, "recent developments" within the scientific disciplines, but the texts themselves never depart substantially from the central theme that scientific knowledge and understanding are stable, their only detectable movement being growth. In what follows, we want to make the idea of subject matter in science problematic. We will show that the view of the fixed nature of subject matter is misleading, and that science and its context are better viewed as shifting.

We begin by summarizing the arguments developed in "A Common Curriculum for the Natural Sciences" (Munby & Russell, 1983). Since writing that chapter, a number of developments have influenced our thoughts about the state of science education. In what follows we describe the widening gap between science and "school science," shifts in science's epistemology and in the linguistic context in which science is taught, the interest expressed in "science for all," and the significance of the epistemology of schools as organizations. What we have learned from these issues does nothing to alleviate the concerns we expressed in our chapter. We remain convinced that science education in schools inadequately portrays how scientists learn and come to know.

---

1 Paper presented at the annual meeting of the American Educational Research Association, Washington, D.C., April, 1987.

2 BITNET addresses: MUNBYH@QUCDN and RUSSELLT@QUCDN

The School of Graduate Studies and Research, Queen's University at Kingston, contributed financial assistance for conference travel expenses.

An Opening Position

In our chapter, "A Common Curriculum for the Natural Sciences" (Munby & Russell, 1983), we followed the lead given by the editors, Fenstermacher and Goodlad, and explored the tension between "common curriculum" and "individual differences" in terms of educational experiences that would enable people to live "rational, moral, and authentic lives." We applied the central concepts of "rational," "moral," and "authentic" to three inter-related aspects of science curricula: (1) science, education, and science education, (2) the science teacher and the teacher's context, and (3) the individual student of science. One of our major themes is captured in a single sentence: "The more we wrestled with these terms, the more we came to see that one could not expect *rational*, *moral*, and *authentic* lives to be a consequence of educational experiences *unless the experiences per se were rational, moral, and authentic*" (Munby & Russell, 1983, p. 162).

Science and Education

In our analysis of science and education we considered the *limits* of science, the *meaning* of science, the role of science in society, and the question of *authenticity* in science education. We argued that "if science gets presented as the epitome of rationality, then it is being misrepresented . . . such a portrayal is *inauthentic* both to science and to education." (p. 165). Here, our goal was to call attention to the risks involved in presenting science *as* rationality. We then argued that "nothing *unique* is being conveyed by the notions of scientific processes and the scientific method" (p. 167), maintaining that schooling generally, not science education specifically, has responsibility for teaching the use of logic in problem solving. "What is *basic* to the logic of *science* is the way it uses language to construct a unique reality" (p. 167), we concluded. An example in which a Grade 4 child disagreed with her teacher's statement that "People are animals" illustrated our point that what is distinctive about science is its specialized use of language within a very powerful way of looking at a broad range of natural phenomena.

> Within this understanding of what science does with language lies the heart of what we find *distinctive* about scientific thinking. Science constructs the world using language in a special way, and employs rules about the generalizability of its constructions, their predictive power and explanatory force, and their necessary public testability. (p. 168)
>
> Our answer to the question about what is basic to an understanding of scientific thinking has to be that science is a way of using language to construct a highly organized and powerful way of looking at the world and understanding it. (p. 169)

We turned next to an analysis of arguments that call for developing "scientific literacy" among students and for fostering positive attitudes toward science. We concluded that there is an important *moral* dimension to science education that presently receives very little of the attention it deserves. It is very easy to assume that scientific literacy could only have positive effects on students and that a positive attitude toward science is desirable, regardless of the evidence on which it is based. One significant result is that the complex and ambiguous relationship between science and society is not being used to develop the "moral" and "authentic" aspects of science education.

We concluded discussion of the concepts of science and education by arguing that the act of teaching tends, by its very nature, to inauthenticity, because of the difficulty of providing the student with a prior basis for deciding whether he or she wishes to become aware of particular scientific knowledge, or of any science at all. Munby's (1984) analysis of the concept of "intellectual independence" is helpful here, calling for teachers to develop students' capacities for making judgments by providing students with relevant assumptions, alternatives, evidence, and arguments.

> If students are denied access to the support for a scientific theory, if they have no way of knowing why a portion of reality is thought to be adequately represented by one model rather than by another, if they are presented with one moral position in the absence of alternatives, and if they are forced to adopt the scientific world view without the option of at least examining alternatives, then the experience loses some of its integrity, tends toward inauthenticity, and leaves the phrase, "Do as I say, not as I do" ringing stridently. (Munby & Russell, 1983, p. 175.)

The Science Teacher's Context

Here, we considered how the context in which a science teacher attempts to teach science can itself be characterized by the terms "rational," "moral," and "authentic." We noted that, with respect to both curriculum development and educational research in general, it seems only too easy to ask teachers to conduct their work in particular ways without inquiring about the *personal teaching context* and its similarities to the contexts that were assumed in curriculum development or observed in research. Without wishing to assign blame, we concluded that the relationship of the developer or researcher to the teacher has been "an excessively rational one, deficient in terms of significant contextual considerations including those indicated by the terms 'moral' and 'authentic'" (p. 177). A similar story is noted in the supervision of teachers' professional duties; traditional practices give minimal attention to contextual features of the classroom setting and take an excessively rational view of how theory can influence practice. The growing use of qualitative research strategies, which are required to study the teacher's context in any detail, is beginning to redress the imbalance and provide new interpretations for the actions for which teachers have often been criticized.

The Individual Science Student

In closing our analysis of "a common curriculum for the natural sciences," we turned to the issue of how the individual student encounters the scientific disciplines. We called for "an entirely fresh approach to the problem . . . one that is true not only to the context of the individuality of teacher and student, but also one which heeds and preserves the special integrity of science education itself" (p. 180). Instead of treating as common some selected core of scientific content, we argued that all students should share in a *common context*, grounded in the nature of science as a discipline and in the provision of instruction that fosters intellectual independence. We also called for enhancing the choices available to students about ways in which science content may be approached. Alternative approaches do exist in commercial materials, but the range of possible alternatives is far greater; science is important to society in many different ways, each a significant line of inquiry, and each providing a unique way of organizing science content. Finally, the selection to be made was left to individual students and their teachers, an inevitable conclusion given our concern that *context* has long been neglected in science education.

> Educationally significant individual differences, says our perspective, are met best by (a) providing students with genuine choices among alternative approaches to a given science subject at a particular grade level, and (b) encouraging teachers to develop those

alternative curriculum approaches which are in concert with their views of what is important about science for the individual students they teach. (p. 183)

The Widening Gap between Science and "School Science"

One of the major and intransigent problems for science education can be found in the advances of present-day science. But the problem is not simply a matter of there being more science. If that were the problem, the solution would be relatively simple: we would have to be sure to cover more content, in the tradition of the fixed nature of the subject matter. But the condition is more complex than so simple a solution can meet. Part of the condition is the increasing sophistication in scientific conceptualizations. The other part covaries with the first, and is the widening of the chasm between those who can comprehend science and those who cannot. An excellent account of this condition is given by Holton (1986), who ·tifies the inability of science to profit from the wise counsel of humanists, and the increasir. ·re of a citizenry to exert political control over science as problems stemming from the s. . He puts it this way:

> As the plane of experience expands through the use of specialized or high-technology observational devices, the public progressively loses access to the phenomena of nature. The connection between phenomena and theory, the theory itself, and the way it is constructed, confirmed, and elaborated are, and have to be, fully controlled by the scientific community, and understanding them comes only with long immersion . . . . Precisely as science progresses toward its declared goal (of building a unified scientific world view) and as the rate of its new triumphs increases, the larger yawns the unnegotiated intellectual separation from those standing on the sidelines. (p. 93)

This directs a challenge at the science education community to develop ways of making science accessible. Here, we see numerous problems. The science of the late 1980's is very different from the science of the 1950's and 1960's, yet there do not seem to have been radical changes in the ways in which the discipline is presented in school science curricula. We still seem bound by the time-honored compartments of physics, chemistry, and biology, and by their juniors, earth or environmental science and "general science." Our view is that nothing short of a major overthrow of this structure can initiate a reversal of the trend toward a scientifically disengaged population.

Of course, there is a sense in which our arguments offer comfort to those who do not see themselves as responsible for the state of science curricula in schools and universities. We wish to counter the comfort with disquiet by arguing that the society's distancing from scientific affairs is not a problem for science educators alone. As Holton shows, the distancing robs the scientific community of the wisdom of its critics and its champions. Society's need for the sagacity and astuteness associated with humane decisions becomes more acute as science becomes more complex and embracing. And so the problem is not restricted to the science curricula, but extends clearly into the curricula of the humanities.

Shifts in Our Understanding of Science's Epistemology

The work of Toulmin (1960), Kuhn (1962), Hanson (1965), and many others has contributed substantially to the "received" view of the nature of science. Yet, despite the efforts of scholars like Schwab (1964), there is comparatively little evidence in science textbooks that any heed has been taken of what is now understood about the nature of science. We drew attention to this startling omission in our chapter (Munby & Russell, 1983), and we argued that epistemology was central to science and so should comprise a core for its curriculum. While we remain convinced that our view is appropriate still, we are obliged to observe that the ground has shifted again, and in a rather unexpected way. Recent feminist scholarship is advancing the case that science's epistemology is gender-biased. Keller's (1985) collection of essays presents an accessible account of the emergence of this bias from the marriage metaphors and domination metaphors she uncovers in Baconian thought. Yet, for Keller, the bias in contemporary science is more far-reaching than what we see expressed in such ideas as man's subjugation of nature--usually female. Indeed, the source of bias is as profound as the implicit links our language and culture encourage among "objectivity," "autonomy," "power," and "masculinity."

> All four of these terms admit of a range of meanings. *Autonomy*, at one end of its range, connotes a radical independence from others, mapping closely on an interpretation of *objectivity* that implies a reductive disjunction of subject from object--an interpretation I have labelled "objectivism." It is this end of the spectrum of objectivity that . . . correlates with a conception of masculinity denying all traces of femininity. Here I will go on to argue that the same interpretation of autonomy also correlates with a conception of power as power over others, that is, with power defined as domination. Thus the linkage between objectivity and domination that feminists have discerned is not intrinsic to the aims of science, or even to the equation of knowledge and power, but rather is the particular meanings assigned to both power and objectivity. In short, it is argued that this linkage is a derivative of the particular biases that are cast by modern Western culture on all aspects of psychological (cognitive as well as emotional) development. (Keller, 1985, p. 97)

In our chapter, we expressed concern for science teaching (and texts) that implicitly denied the discipline's epistemology and concealed the central role played, subjectively, by humans in constructing a scientific reality out of our phenomenal world. Such deception, we urged, was so serious as to warrant our questioning if science education was a misnomer, and if "science indoctrination" might be more apt. From Keller, we are learning that the epistemological deception invokes a further lie by promoting masculinity at the expense of femininity.

If Keller's analysis is adequate, then at least two important avenues become available to science educators. The first of these is research. Here, it becomes obvious that we need to question more deeply the reasons that girls are less attracted to science programs and achieve less in them than boys. Quite possibly, the standard explanations tying the phenomena to aptitude, attitude, and careers are jejune. We prefer to ask why any adolescent female would wish to subscribe to an enterprise whose fundamental metaphysic constitutes an implicit assault on her gender identity. The second avenue for science educators is curriculum. If Keller is right, science curricula need to go further than we thought when we were arguing that more than lip service be paid to the nature of science whenever science was taught. One typical response to the realization that female scientists are under-represented in science courses is to advocate the inclusion, in an already over-stuffed curriculum, of sections on women in science. With Keller's help, we see curricular nodding of this kind as inappropriate and potentially offensive.

Science and Shifting Linguistic Contexts

Recent and exciting work on alternative conceptions has rekindled our own concern for what children bring with them to the science classroom. In this section, we wish to explore how the language children bring to science education is changing in a way that may make science teaching more obscure to them. Here, our reference point is metaphor, and our thinking is stimulated by papers by Pope and Gilbert (1983) and Holton (1984), and by Munby's (1986) interest in metaphorical speech.

A substantial part of the paper by Pope and Gilbert (1983) is given to raising empirical questions that are derived from considering the place of metaphor in teachers' efforts to render the incomprehensible more accessible. The questions themselves are seductive, so it is worth reproducing some of them here.

> How does a teacher's view of the nature of subject matter govern the role given to metaphor during teaching? (Pope & Gilbert, 1983, p. 253)
>
> How does the form of presentation of a metaphor by a teacher affect the use to which the metaphor is put by a student? (p. 255)
>
> To what extent is a student able to share a teacher's metaphors and use them to increase understanding? (p. 257)

While others, Sutton (1981) for example, have considered metaphors in teaching, little heed has been accorded the linguistic context in which these are heard by students. The questions posed by Pope and Gilbert assume greater significance when context is considered, as we show below.

The linguistic context to which we refer is that part of our language that we usually recognize to be scientific. But this is an oversimplification, as Holton's paper suggests (1984). He presents a long list of exotic metaphors that have crept into our language, and that constitute the "metaphoric background" for students:

> The Big Dipper, the black hole, the big bang and the big crunch. The harmony of the spheres, the expanding universe, the clockwork universe, attraction and repulsion, inertia, perhaps Schrödinger's cat, left-handed neutrinos, parity breakdown, coloured and flavoured quarks, gluons, charm, and God playing (or not playing) dice. Also, the heat death, kingdoms of animals and plants, computers that crash or refuse commands, broken symmetry, families of elements, daughter and grand-daughter isotopes in radio-active decay, negative feedback, circulation of blood, the tangled bank, the selfish gene, degenerate quantum states, and "everything is relative" . . . . The main trouble with this *bouillabaisse* is that metaphors do not carry with them any clear demarcations of the areas of their legitimacy. They may be effective tools for scientists, but pathetic fallacies for students. (p. 102)

Just as our understanding of the context of science education shifts with our emerging knowledge of children's alternative conceptions, so our understanding of the linguistic context shifts when we see the potential chaos of introducing explanatory metaphors in science classrooms to students whose ordinary language is replete with scientific metaphors that may be improperly interpreted. The chaos increases, of course, when we recognize that the linguistic context itself shifts as science creates new metaphors.

The Seductiveness of "Science for All"

In our chapter (Munby & Russell, 1983), we noted the problematic nature of the phrase "scientific literacy." Here, we call attention to the seductive nature of the "Science for All" slogan. Fensham (1986) has argued that attempts to bring general science education to a level where it meets all students have failed, and that the curricula resulting from these efforts are essentially science for the elite. He blames the failure on the tendency of science education to constitute an induction into science, sometimes as a profession, and argues for an approach that would focus on learning "*about* and *from* science" (p. 14). Fensham views this as a way to emphasize that the "all" in the slogan refers to those outside the discipline. He offers two proposals to effect this change:

1. That inductive or elitist science education must be confined to an upper level of schooling.

2. That we recognize science as a "widely variegated source of human knowledge and endeavor" (p. 13), and that we try to bring scientific material to courses outside of the discipline itself--science teachers then become "couriers."

Next, he proposes that we establish and ruthlessly apply criteria for selecting science content. Two criteria are offered as illustrative:

> 1. Aspects of science should be included that, in the society concerned, have a high probability of being used in a relatively short time by students in their daily lives *outside* school.
>
> 2. Aspects of natural phenomena should be included which exemplify easily and well *to students* the excitement, novelty and power of scientific knowledge and explanation. (Fensham, p. 15)

Examples illustrating the application of these criteria are Senses and Measurement, The Human Body, Health, Nutrition and Sanitation, Food, Ecology, Resources, Population, Pollution, and Uses of Energy. The sense we have of what is emerging here is the idea that science produces infallible information that is to be transmitted without its epistemological and corrective context. There is nothing very wrong with transmitting information, of course. But, unless something is done to provide recipients with an understanding of what trust to place in the information, we run the risk of completely distorting science for all. Indeed, Fensham's proposals appear to have the potential for undercutting all the points that we have been making about the intellectual context of science and about the centrality of this context to science education. Fensham's version of "Science for All" might be interpreted as "True Information for All"

To our way of thinking, Fensham's proposals create problems that extend further than the obliteration of epistemological considerations in the curriculum, which we have shown to portray science inauthentically (Munby & Russell, 1983). One problem is that Fensham's proposals seem not to account for major or even minor shifts in our understanding of the validity of scientific information. Obsolescence is handled by this vision of "Science for All" no better than it is handled by traditional conceptions of science education. A further problem concerns the seductive quality of the list of illustrative topics that Fensham presents, and this is tightly bound to an unexamined element of the slogan itself. Fensham treats "Science for All" as if it meant the science information to which *all*, noting geographic differences, should be exposed. This meets the concern for separating the science-bound students from those not so inclined, but it does nothing whatsoever to honor the other ranges of differences presented in classes of children and in schools of classes. Differences in aptitude, interest and aspiration get washed aside. Instead of recognizing such differences and calling for suitable curriculum alternatives in schools, Fensham offers a list of likely topics in science. But the list harbors an implicit assumption that we think has a dangerously seductive appeal. *The assumption is that a list of topics can be generated that can meet the needs of all students.* Our position is now as it was before (Munby & Russell, 1983): we believe that it is possible to provide science education to all students, but not by providing the *same* science education to all students.

The Epistemology of Science: The Neglect is Not Deliberate

In a variety of interesting ways, over a period of many years, "outsiders" with knowledge of issues within the philosophy of science have indicated that science education in our schools commonly neglects epistemological features of science. Put more straightforwardly, the issue of "How do we know?" is ignored, discouraged, and treated as inappropriate. Kilbourn (1982) speaks of "epistemological flatness" in science lessons that he observed. Brush (1974) tried to make the point by asking whether the history of science should be "rated X," implying that students may need to be protected from learning how science really developed. In the national study of science education carried out by the Science Council of Canada, position papers were produced, along with reports of quantitative and qualitative data about science teachers and their classrooms. One of the position papers dared to use the word "epistemology" in its title (Nadeau & Desautels, 1984), yet Canadian children continue in their epistemological innocence, just as do children in other countries. Issues as apparently simple as the fact that the human chromosome count dropped from 48 to 46 in the 1950s, or that Avogadro's Number has not always been pegged at 6.02×10^{23} are treated as uninteresting and unimportant.

It would be only too easy to blame teachers, and teachers alone, for this neglect of epistemological features of science. But such an explanation is as misleading as it is simple; it builds on the "dim view" of teachers' knowledge that is widespread in our culture (Feiman-Nemser & Floden, 1986). Here, we suggest that the epistemology of science is not deliberately neglected by teachers; rather, the epistemology of the school as an organization overwhelms epistemological features of science, or of any other disciplined body of knowledge. The makings of this alternative explanation become apparent when Schön (1983) applies his contrast between "technical rationality" and "reflection-in-action" to the school as an organization (pp. 329-336). Both in terms of personnel and in terms of the curriculum, the school is organized on the assumptions of "technical rationality." From this perspective, knowledge obtained by research is passed from experts to those who will use the knowledge, and those who receive the knowledge are neither required nor expected to show interest in how the knowledge was developed. While "technical rationality" requires no interaction between theory and practice, "reflection-in-action" depends on it, focussing attention on the interplay between action and the actor's frames for constructing the situation in which action occurs. These features of teachers' and students' thinking are receiving increasing attention among educational researchers, but the school as an organization neglects them.

Our view of teachers can be a more kindly one when we focus attention on features of the organization within which they work, rather than on the individuals themselves. Neglect of epistemological features of science is not surprising but rather is predictable when we notice that the curriculum is "handed down" to teachers, just as they are expected to "hand down" the curriculum to their students. Two of the central expectations placed on teachers are the requirement that they cover the prescribed curriculum content and the requirement that they evaluate their students' success in mastering that curriculum content. Both requirements are central to the process by which students gain access to the next level of schooling and, in the name of such fundamental values as fairness and equality of opportunity, these requirements must be met. These pressures are most easily satisfied in an environment that is "epistemologically flat," an environment uncluttered by issues of how knowledge develops or how learning occurs. The life of the organization is smoothest when "reflection-in-action" by teachers and students is ignored. Puzzling and surprising aspects of teaching are as neglected in adults' communication in schools as those same aspects of learning are neglected in teacher-student and student-student communication within classrooms.

The Challenge is the Neglect

In this paper, we have elaborated on our concern that science education be rational, moral, and authentic, as we argued previously (Munby & Russell, 1983). We have considered the discipline of science from the perspectives of how science is known and how science is learned, and we find that these perspectives do not appear to inform the teaching of science in our schools. How we teach science neglects how we know science and our understanding of how children learn science. We suggest that this situation can be explained not by criticizing teachers but by examining the curricular position that scientific knowledge is fixed, and by examining epistemological features of the school environments in which teachers and children are situated. The persistence of the myth that subject matter is fixed has the potential for misleading science education, its teachers, and its students. Until the myth is defused, and until the epistemological features of schools begin to change, we anticipate that science education experiences in schools will remain very much as they are: they will misrepresent the enterprise, will appeal to few students, will confuse others, will divert still more, and will fail to offer all students appropriate avenues for exploring science and how we know it.

References

Brush, S. (1974). Should the history of science be rated X? *Science, 183*, 1164-1172.

Fensham, P. (1986, September). Science for all. *Newsletter of Division B, American Educational Research Association*, 6-17.

Feiman-Nemser, S., & Floden, R. (1986). The cultures of teaching. In M. Wittrock (Ed.), *Handbook of research on teaching* (3rd ed.), (pp. 505-526). New York: Macmillan.

Fenstermacher, G. & Goodlad, J. (Eds.), *Individual differences and the common curriculum. The Eighty-second Yearbook of the National Society for the Study of Education, Part I.* Chicago: University of Chicago Press.

Hanson, N. (1965). *Patterns of discovery*. Cambridge: Cambridge University Press.

Holton, G. (1984). Metaphors in science and education. In W. Taylor (Ed.), *Metaphors of education* (pp. 91-113). London: Heinemann.

Holton, G. (1986). The advancement of science and its burdens. *Daedalus, 115*(3), 77-104.

Keller, E. (1985). *Reflections on gender and science*. New Haven, CT: Yale University Press.

Kilbourn, B. (1982). Curriculum materials: Teaching, and potential outcomes for students: A qualitative analysis. *Journal of Research on Science Teaching, 19*, 675-688.

Kuhn, T. (1962). *The structure of scientific revolutions.* Chicago, IL: Chicago University Press.

Munby, H. (1984). Analyzing teaching for intellectual independence. In H. Munby, G. Orpwood, & T. Russell (Eds.), *Seeing curriculum in a new light: Essays from science education* (pp. 11-33). Lanham, MD: University Press of America.

Munby, H., (1986). Metaphor in the thinking of teachers: An exploratory study. *Journal of Curriculum Studies. 18,* 197-209.

Munby, H., & Russell, T. (1983). A common curriculum for the natural sciences. In G. Fenstermacher & J. Goodlad (Eds.), *Individual differences and the common curriculum. The Eighty-second Yearbook of the National Society for the Study of Education, Part I* (pp. 160-185). Chicago: University of Chicago Press.

Nadeau, R., & Desautels, J. (1984). *Epistemology and the teaching of science: A discussion paper.* Ottawa: Science Council of Canada.

Pope, M. & Gilbert, J. (1983). Explanation and metaphor: Some empirical questions in science education. *European Journal of Science Education, 5,* 249-261.

Schön, D. (1983). *The reflective practitioner: How professionals think in action.* New York: Basic Books.

Schwab, J. (1964). The structure of the natural sciences. In G. Ford & L. Pugno (Eds.), *The structure of knowledge and the curriculum* (pp. 31-49). Chicago: Rand McNally.

Sutton, C. (1981). Metaphorical imagery: A means of coping with complex and unfamiliar information in science. *Durham and Newcastle Research Review, 9,* 216-222.

Toulmin, S. (1960). *The philosophy of science: An introduction.* New York: Harper and Row.